

“Enhanced Wellbore Stabilization and Reservoir Productivity with Aphron Drilling Fluid Technology”

Topical Report: Task 4.1 Correlation of Capillary Suction Time with Leak-Off Behavior

by

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Introduction

Core Leak-off tests are commonly used to ascertain the ability of a drilling fluid to seal permeable rock under downhole conditions. Unfortunately, these tests are expensive and require a long time to set up. To monitor fluid invasion trends and to evaluate potential treatments for reducing fluid invasion on location, a simpler screening test is highly desirable.

The Capillary Suction Time (CST) Test has been used since the 1970's as a fast, yet reliable, method for characterizing fluid filterability and the condition of colloidal materials in water treatment facilities and drilling fluids. For the latter, it has usually been applied to determine the state of flocculation of clay-bearing fluids and to screen potential shale inhibitors.

In this work, the CST method was evaluated as a screening tool for predicting relative invasion rates of drilling fluids in permeable cores. However, the drilling fluids examined -- DRILPLEX, FLOPRO, and APHRON ICS -- are all designed to generate low fluid loss and give CST values that are so high that fluid invasion comes to be dominated by experimental artifacts, such as fluid evaporation. As described in this work, the CST procedure was modified so as to minimize such artifacts and permit differentiation of the fluids under investigation.

Objectives

Evaluate the potential for Capillary Suction Time to predict rates of invasion of APHRON ICS and other drilling fluid systems into permeable formations.

Project Description

The Capillary Suction Time (CST) Test, a rapid and cost-effective technique, is commonly used to ascertain the state of flocculation of a fluid and its ability to control filtration through permeable media. The standard CST method breaks down, however, for highly dispersed low-filtration-rate fluids.

In this study, a Modified CST procedure was developed that eliminates this problem and is shown to provide results that correlate well with conventional static Core Leak-Off test results for drilling fluids. This procedure calls for measurement of the travel distance of the fluid front, or CSD, in a specified amount of time.

For drilling fluids that seal via similar mechanisms, the Modified CST Test can be used to predict the trend in the rate of fluid invasion into permeable formations. Fluids which seal via different mechanisms yield different CSD vs. Leak-Off correlations, most likely because of differences in spurt loss behavior.

Conclusions

Using a Modified CST procedure that generates a measurement of CSD (the distance that the fluid front travels in 60 min), it has been demonstrated that CSD for low-fluid-loss drilling fluids correlates with Core Leak-Off test results and obeys standard static filtra-

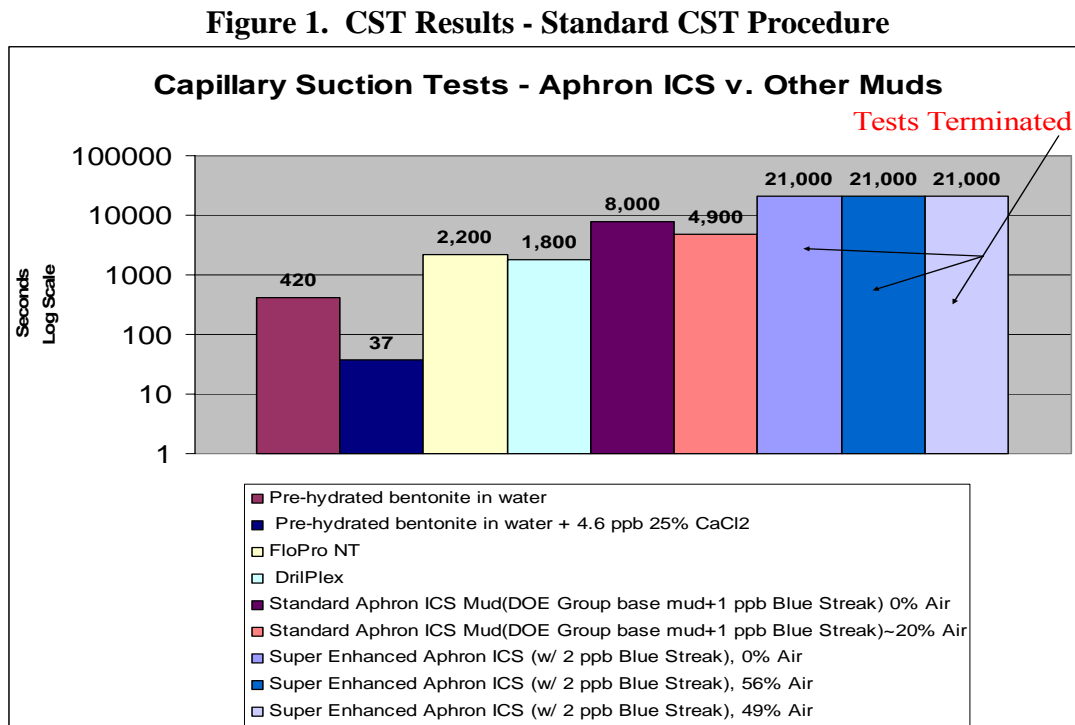
tion theory. The Modified CST procedure has promise as an on-site tool to monitor fluid invasion trends and evaluate potential treatments for reducing fluid invasion.

Aerated Enhanced APHRON ICS and DRILPLEX drilling fluids generate lower CSD and Core Leak-Off than solids-free APHRON ICS and FLOPRO drilling fluids. Because the sealing mechanism varies with type of drilling fluid, different CSD vs Core Leak-Off correlation curves must be used for each fluid system. System-to-system variability of the CSD vs Core Leak-Off correlation is likely due to the greater impact that spurt loss has on Core Leak-Off than on CSD.

For a given drilling fluid system, CSD and Core Leak-Off correlate inversely with LSRV, i.e. $CSD \text{ and Leak-Off} \propto (LSRV)^{-1}$. In addition, additives such as $CaCO_3$ (and air in the Enhanced APHRON ICS Drilling Fluid) decrease Core Leak-Off and, to a lesser extent, CSD.

Experimental Approach

The Modified CST and Core Leak-Off test methods utilized in this project are described in Appendices A and B at the end of this report. In all cases, the fluid samples were blended with a Prince Castle mixer and hot-rolled for 16 hours at 150°F. Initial tests were performed using the standard CST method.¹ Various mud types were evaluated, and the results are given in Figure 1.



The fluids with very long CST values cannot be very clearly differentiated, and artifacts such as evaporation of water from the blotting paper control the rate of advance of the

filtrate. It was determined that CST values higher than a few thousand seconds are fraught with unacceptably high error. For these fluids, the Modified CST test appears to provide a much more precise and accurate way to monitor relative filtration rates. As described in Appendix A, the Modified CST test involves measuring CSD, the distance in mm traveled by the fluid in a given time period. Results for the APHRON ICS Drilling Fluid (with and without entrained air) appear in Table 1 in Appendix A.

Four samples of each system were blended, and the concentration of viscosifier specific to each system was varied. The systems utilized were: Standard APHRON ICS, Super Enhanced APHRON ICS (SE APHRON ICS), FLOPRO, and a DRILPLEX. The Standard APHRON ICS system is converted to the SE APHRON ICS via addition of small quantities of three products: Aphronizer A, Aphronizer B and Plasticizer. All of the drilling fluids were run as “solids free” systems, but some tests were also run with samples containing 30 ppb of CaCO₃ with a nominal particle diameter of 40 µm. The corresponding Low-Shear-Rate Viscosity (LSRV), Leak off, and CSD were measured for each one of these samples. All of the tests were run at room temperature. LSRV was measured with a Brookfield LV-II+ Viscometer at 0.06 sec⁻¹ using a L3 spindle. The Core Leak-Off tests were run with 1,000 psi confining pressure, 500 psi inlet pressure and no back pressure, using 2-in long Aloxite cores of about 5 darcy air permeability. In all cases, the CSD values used for the correlations were those measured at 60 min (half of the total testing time). The CSD vs Leak-Off correlations obtained with the 30-min CSD data were similar to these, but the CSD data appeared to be somewhat less precise. The correlations obtained with the 90-min and 120-min data were also similar to those obtained with the 60-min data and did not appear to provide any greater precision. Consequently, the 60-min CSD values were used for all of the correlations.

Results

Filtration in the Modified CST (CSD) Test

“Static filtration takes place when the mud is not circulated, and the filter cake grows undisturbed”.²

If a unit volume of a stable suspension of solids is filtered against a permeable substrate (paper or core in our case), and x volumes of filtrate are expressed at time t, then 1 – x volumes of cake will be deposited on the substrate. As a simplifying approximation, the rate of growth of the filter cake is assumed to be proportional to the rate of growth of filtrate. Therefore, if Q_c be the volume of the cake, and Q_w the volume of the filtrate:

$$\frac{Q_c}{Q_w} = \frac{1-x}{x} = R \quad (1)$$

Where R is a constant. Now, the area of the filter cake, A, is constant in linear static filtration, such as API Fluid Loss and Core Leak-Off tests. It is also constant in a CSD test, though the filtrate itself expands radially along the plane of the paper. Q_f is given by the product of A and the thickness of the filter cake:

$$Q_f = Ah$$

Thus,
$$h = R Q_w / A \quad (2)$$

Now, Darcy's law states

$$\frac{dq}{dt} = \frac{k \Delta P A}{\mu h} \quad (3)$$

Where k = permeability of the filter cake (darcy), ΔP = differential pressure across the cake (atm), μ = viscosity of the filtrate (cP), h = thickness (cm), q = volume of filtrate (cm^3), and t = time (sec).

Therefore,

$$\frac{dq}{dt} = \frac{k \Delta P A^2}{\mu R Q_w}$$

Integrating,

$$Q_w^2 = 2k \Delta P A^2 t / \mu R \quad (4)$$

Unifying the constant terms results in

$$Q_w^2 = K t \quad (5)$$

or,

$$Q_w = K' t^{1/2} \quad (6)$$

Where K and K' are proportionality constants. Equation (6) governs filtration under static conditions.²

In the Modified CST method (CSD), the distance that the fluid travels, d , is proportional to Q_w . Thus,

$$d = K'' t^{1/2} \quad (7)$$

Some results for two types of APHRON ICS Drilling Fluids are plotted in this fashion in Figure 2.

The results in Figure 2 for the two samples of Deaerated APHRON ICS Drilling Fluids demonstrate the high reproducibility of the Modified CST test.

The linearity of the $t^{1/2}$ plots shows that CSD follows static filtration theory. It does not necessarily follow, however, that CSD will correlate with core Leak-Off behavior. Key differences between core Leak-Off and Modified CST tests include saturation of the pore network (wet vs. dry), the nature of the filter medium (core vs. paper), differential pressure (elevated inlet pressure vs. ambient pressure), and possibly temperature.

The effect of saturation of the pore network with the base fluid is manifested as a displacement in the apparent "spurt loss." Spurt loss is generally defined as the loss of whole mud that occurs initially during fluid invasion, i.e. prior to formation of a fully established filter cake. This is given approximately by the y-axis intercept on the $t^{1/2}$ plot. In the mathematical treatment of static filtration given above, spurt loss is assumed to be

negligible. However, spurt loss is known to be significant in permeable rocks. Furthermore, “a low fluid loss and a dry cell with high hold up volume will cause a negative y-axis intercept”.³ To prove this, two CSD tests were run, one using dry filter paper and one using wet filter paper. The system used was Deaerated SE APHRON ICS Drilling Fluid with 5 ppb viscosifier. The results are shown in the Figure 3.

Figure 2 - CSD vs. Square Root of Time

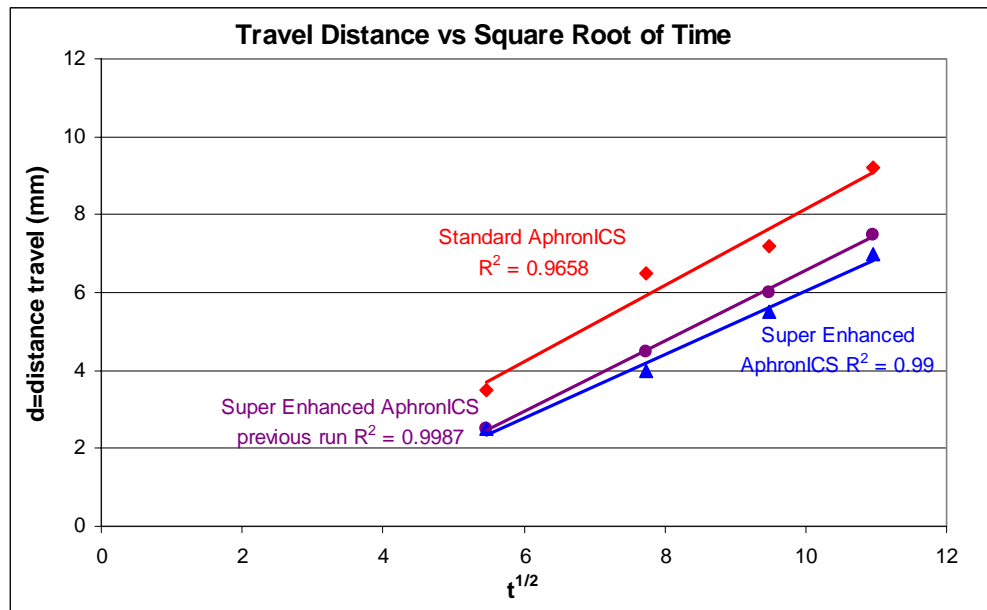
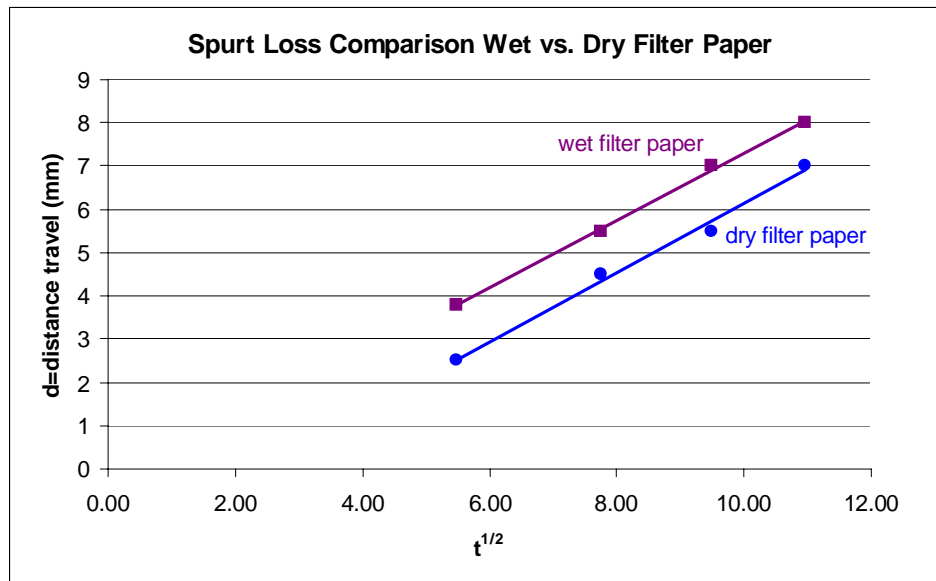


Figure 3 - CSD for Wet vs. Dry Filter paper - Deaerated SE APHRON ICS



It is evident from Figure 3 that, when the paper is saturated with water at the start of the test, the straight line plot for the dry filter paper is displaced upwards about one unit. The spurt loss changes from negative to approximately zero, thus confirming the role played by the interstitial fluid in the paper.

The effects of the nature of the filter medium and differential pressure are more complex. Once a filter cake is well established, the filtration rate is not expected to be affected very much by the nature of the filter medium (paper vs. core), since fluid flow is controlled entirely by the permeability of the cake. Conversely, spurt loss is dominated by Darcy flow, Equation (3), where k and h are now the permeability and thickness of the filter medium, respectively, and μ is the viscosity of the whole mud. Each mud system has a different viscosity profile, which will in turn produce a different rate of spurt loss. In addition, different concentrations and size distributions of particulate matter in the mud will affect the spurt loss period (the length of time of the spurt loss phase). Thus, total spurt loss, as given by the product of the spurt loss rate and spurt loss period, will vary from mud to mud. The higher the permeability of the filter medium, the greater will be the spurt loss and the variability in spurt loss from mud to mud. Thus, the effects of the nature of the filter medium and pressure differential are expected to be manifested in a higher spurt loss for the Core Leak-Off tests vs. the CSD tests. This will undoubtedly lead to different correlations of Core Leak-Off vs. CSD for each mud system,^{4,5} as demonstrated later in the present report.

The results for all of the Modified CST (CSD) and core Leak-Off tests are shown in Table 1.

Table 1 - Summary of LSRV, CSD and Core Leak-Off Test Results

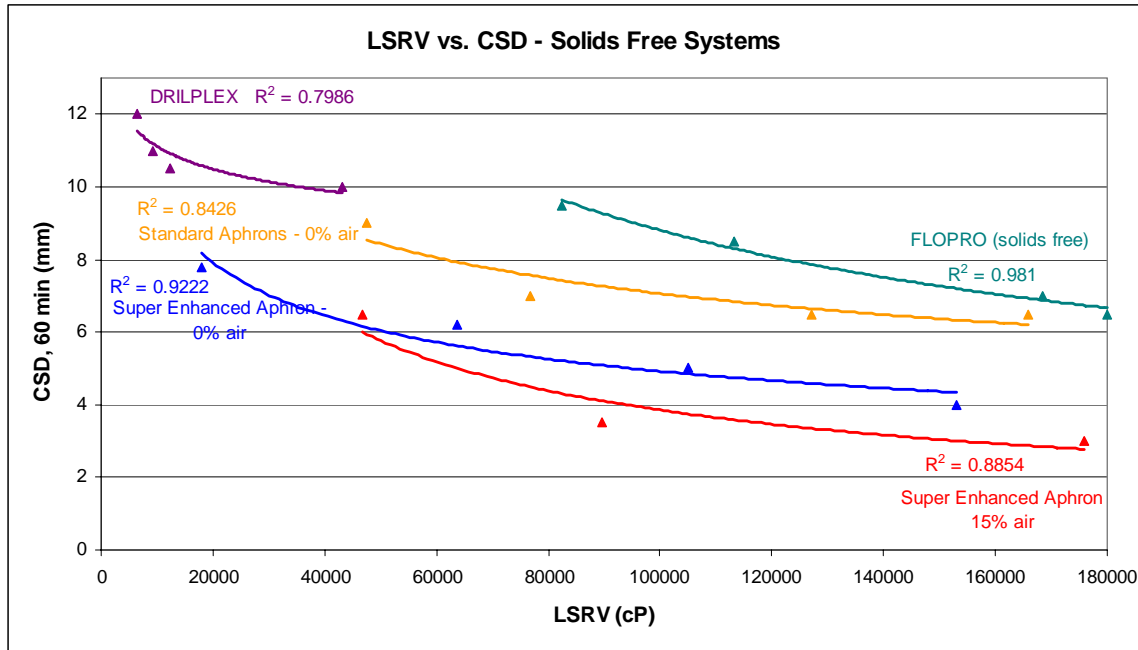
Drilling Fluid System	LSRV (cP)	CSD @ 60 min (mm)	Leak-Off (mL)
FLOPRO			
Sample 1: 2.25 ppb Viscosifier	82,382	9.5	101.8
Sample 2: 2.60 ppb Viscosifier	113,200	8.5	92.2
Sample 3: 2.85 ppb Viscosifier	168,400	7.0	69.3
Sample 4: 3.15 ppb Viscosifier	180,000	6.5	63.1
DRILPLEX			
Sample 1: 0.18 ppb Polymer	6,400	12.0	20.3
Sample 2: 0.40 ppb Polymer	9,200	11.0	11.8
Sample 3: 0.80 ppb Polymer	12,400	10.5	11.0
Sample 4: 1.20 ppb Polymer	43,200	10.0	7.9

Aerated SE APHRON ICS			
Sample 1: 2.50 ppb Viscosifier	46,800	6.5	24.5
Sample 2: 3.50 ppb Viscosifier	89,600	3.5	14.9
Sample 3: 5.00 ppb Viscosifier	176,000	3.0	12.4
FLOPRO + 30 ppb 40-μm CaCO₃			
Sample 1: 2.25 ppb Viscosifier	62,387	6.0	2.9
Sample 2: 2.60 ppb Viscosifier	168,800	6.0	4.4
Sample 3: 3.50 ppb Viscosifier	206,400	6.0	4.1
Aerated APHRON ICS + 30 ppb 40-μm CaCO₃			
Sample 1: 5.0 ppb Viscosifier	169,000	2.0	1.2
Deaerated SE APHRON ICS			
Sample 1: 2.5 ppb Viscosifier	17,996	7.8	156.8
Sample 2: 3.5 ppb Viscosifier	63,586	6.2	79.5
Sample 3: 4.2 ppb Viscosifier	105,000	5.0	61.0
Sample 4: 5.0 ppb Viscosifier	153,000	4.0	28.8
Deaerated APHRON ICS			
Sample 1: 2.5 ppb Viscosifier	47,590	9.0	210.8
Sample 2: 3.5 ppb Viscosifier	76,784	7.0	39.6
Sample 3: 4.2 ppb Viscosifier	127,000	6.5	33.9
Sample 4: 5.0 ppb Viscosifier	166,000	6.5	24.6

Correlations of CSD and Core Leak-Off vs. LSRV

The effect of LSRV on CSD (see Table 1) is shown in Figure 4.

Figure 4. CSD vs. LSRV for All the Systems



All of the curves in Figure 4 follow power law trends fairly well, though it appears that the curves cannot be unified into a single model, i.e. each fluid system appears to follow a different power law expression. The APHRON ICS systems gives lower CSD values than the DRILPLEX and FLOPRO systems. Aerating the SE APHRON ICS lowers the CSD even more. The air in the APHRON ICS systems is present in the form of pressure-resistant bubbles called aphrons, which have been shown to function as an invasion control agent.⁶

Figure 5 shows the correlation of Core Leak-Off vs. LSRV for all the data.

As was the case for the CSD correlations, Core Leak-Off appears to follow a power law trend with respect to LSRV. Again, it does not seem possible to be able to unify the curves; indeed, the curves appear to be considerably more scattered than were the CSD vs LSRV curves. As discussed in the previous section, this is likely the result of spurt loss being more variable for invasion into a core than for invasion into blotter paper. This is especially evident for the DRILPLEX system, which exhibits the lowest Core Leak-Off, yet the highest CSD. The sealing mechanism of this fluid involves a special polymer-clay network that is thought to be particularly effective at reducing spurt loss.⁷

Core Leak-Off vs. CSD

Figure 6 shows the correlation of Core Leak-Off vs. CSD for all the systems.

Figure 5. Core Leak-Off vs LSRV

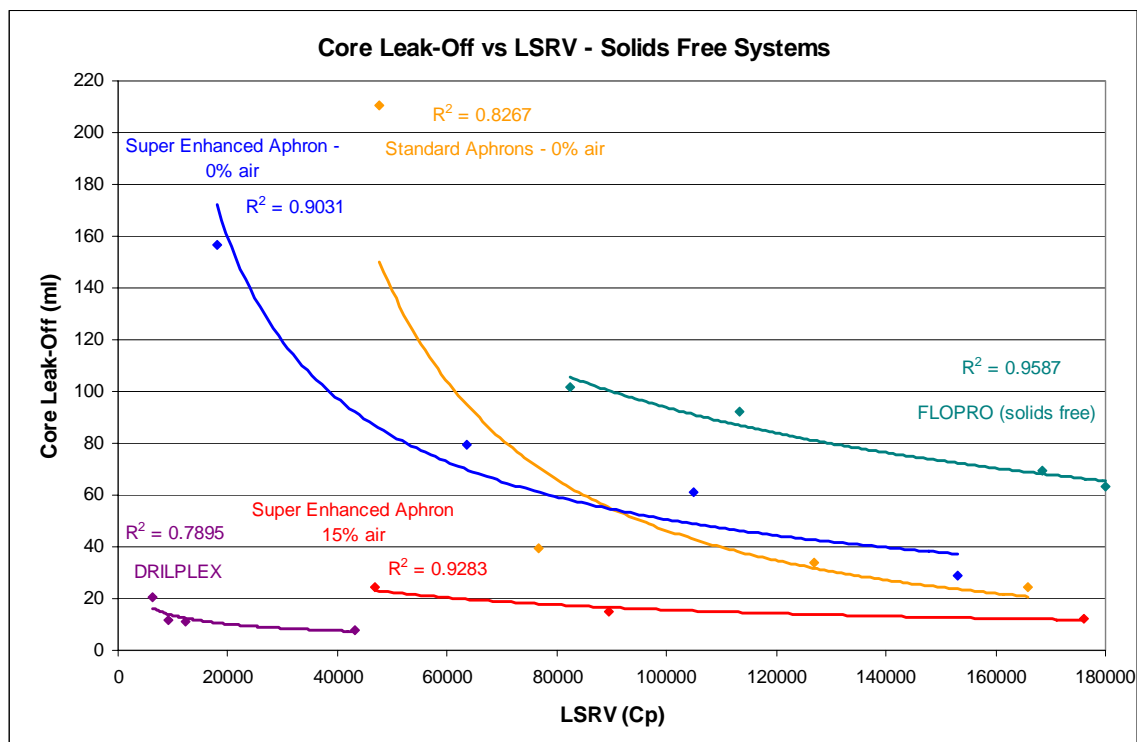
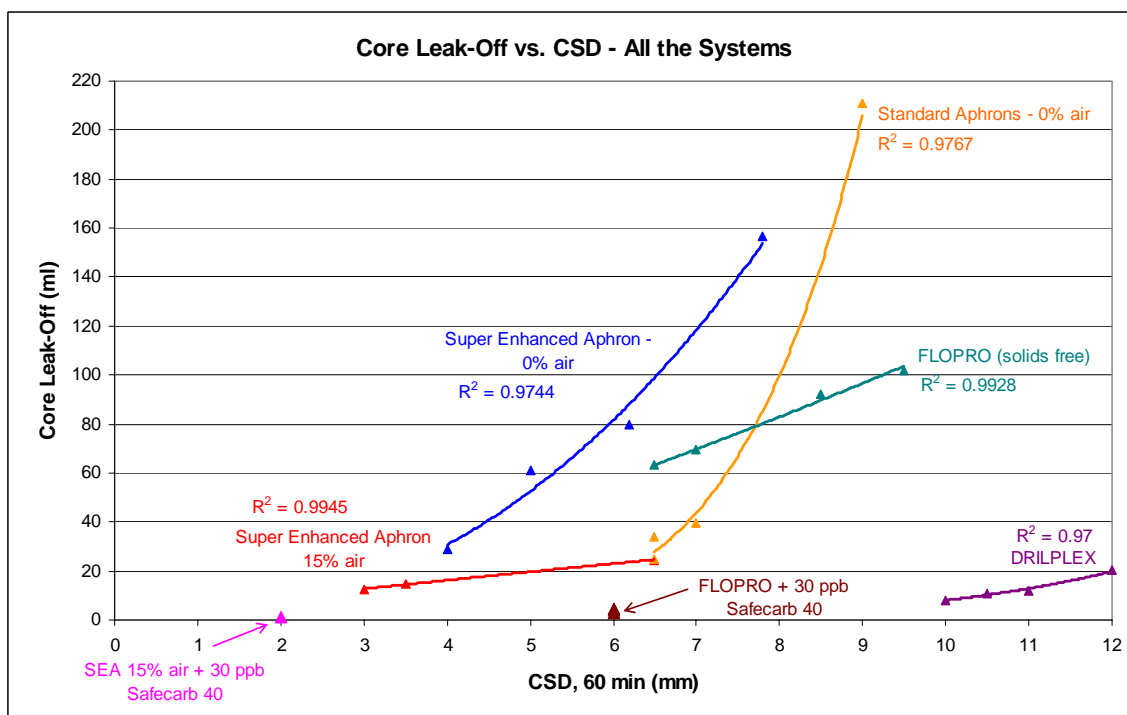


Figure 6. Core Leak-Off vs CSD



As expected from previous discussions and borne out by Figure 6, there is a fair correlation between CSD and Core Leak for individual fluid systems, but there is no unifying correlation curve for all of them.

Addition of CaCO_3 to the FLOPRO and the Enhanced APHRON ICS systems reduces both Leak-Off and CSD. Likewise for addition of air to the Enhanced APHRON ICS.

From the results shown in Figure 6, it appears that CSD and Core Leak-Off for any given fluid system correlate well enough to approximate the value of the Leak-Off of a particular system based on its CSD value.

Thus, the value of CSD measurements is expected to lie in monitoring of fluid invasion trends and evaluation of potential additive treatments.

Nomenclature

BHT = Bottom-Hole Temperature

CSD = capillary suction displacement (distance traveled by the fluid front)

CST = capillary suction time

LSRV = low-shear-rate viscosity at 0.06 sec⁻¹

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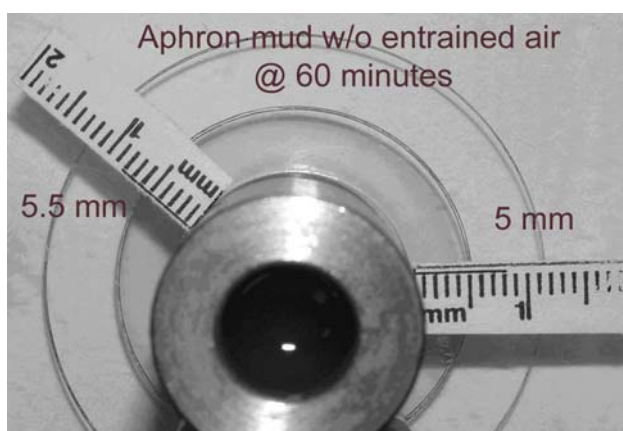
APPENDIX A

Modified CST (CSD) Procedure

For fluids with very long CST's – typically more than a few minutes for the fluid to travel between the two conducting rings – the distance traveled from the sample cup within an arbitrary time period (30, 60, 90 and 120 min was used in this work) provides an accurate relative assessment of the permeability of the filter cake:

- Two 2-cm (20 mm) rules are attached to the top of the transparent cover (see Figure 7).
- The 1.8 cm opening of the test cylinder is placed against the filter paper.
- Five mL of the test mud is placed into the cylinder using a 5 mL syringe.
- The migration of the mud fluid is recorded every 30 minutes for 2 hours.
- The results are expressed in distance (mm), or CSD, versus time (min). At least two readings from different points around the cylinder are taken at each time and averaged.

Figure 7. Modified CST (CSD) Apparatus



Results obtained with a deaerated APHRON ICS and an aerated APHRON ICS are shown in Table 2. Sometimes the filtrate did not migrate uniformly in all directions, as noted by the ranges in CSD.

Table 2. Some Results of Modified CST Test

	Migration Distance CSD			
Fluid	30 min	60 min	90 min	120 min
Deaerated APHRON ICS	2 - 3	5 - 5.5	6 - 7.5	7.5 - 8.5
Aerated APHRON ICS	2	3	3 - 5	3 - 6

APPENDIX B

Leak-Off Test Procedure

The apparatus is shown in Figure 8. The test procedure employs a constant Inlet Pressure of 500 psig and no back-pressure (Outlet Pressure of 0 psig) and is carried out at the same temperature as the CSD tests, i.e. ambient temperature:

- Heat oven to appropriate BHT.
- Apply 500 psig to the piston port.
- Close off piston port (where 500 psig will still be active).
- Open confining port and apply 500 psig.
- Open piston port (both ports will be open at this point).
- Continue to apply pressure until it reaches 500 psig above hydrostatic pressure.
- Apply appropriate reservoir pressure (Back Pressure).
- Open computer program and begin to collect data.
- Apply appropriate mud pressure via accumulator while valve to seal tester is shut.
- Open mud pressure valve to seal tester to start test.
- Collect for 30 min.
- Release pressures in reverse order of application.
- Results are reported as leak-off (in grams) of fluid on a digital balance. This is converted to volume (mL) from the density of the leak-off fluid, the dead volume (water between core and mud sample) is subtracted, and the result is reported as the Net Leak-Off.
- The degree of invasion can also be calculated as

$$\% \text{ Invasion} = [(\text{Pore Vol.} - \text{Net Leak-Off}) / \text{Pore Vol.}] \times 100\%$$

Figure 8. Core Leak-Off Test Apparatus

